Satellite Retrieval of Surface Air Temperature, Humidity, and Evapotranspiration using AMSR-E and MODIS

L.A. Jones[1,3], J.S. Kimball[1,3], Q. Mu[3], K.C. McDonald[2]

[1] Flathead Lake Biological Station, The University of Montana
(lucas@ntsg.umt.edu; Phone: +1-406-243-6220)
[2] Jet Propulsion Laboratory, California Institute of Technology
[3] Numerical Terradynamic Simulation Group, The University of Montana

Summary:

Regional evapotranspiration (ET) is a critical component of terrestrial water and energy budgets and essential for understanding land-atmosphere interactions. Surface air temperature and humidity (measured as vapor pressure deficit VPD) are key variables for determining evaporative demand and canopy stomatal conductance, and energy fluxes. We developed a satellite remote sensing algorithm for estimation of ET using optical information on vegetation canopy cover from MODIS and passive microwave daily air temperature and VPD information from AMSR-E. Air temperature is estimated using AMSR-E dual-polarized brightness temperatures at two frequencies from ascending and descending overpasses that adjust surface emissivity- for the effects of vegetation biomass. VPD is estimated by using minimum daily air temperature is used as a surrogate for the daily dewpoint. Retrieval performance is analyzed for 453 WMO meteorological stations located in the Northern Hemisphere, while ET model performance is assessed using in situ weather stations and a North American latitudinal transect of eddy covariance flux towers representing grassland, boreal forest and tundra. An error sensitivity analysis is conducted to determine the range of ET accuracy given input temperature uncertainty. The AMSR-E based temperature accuracies (RMSE) for WMO weather stations are within 3.6 K and VPD correspondence of 0.28 kPa for forests and 0.44 kPa for non-forest, although site to site bias in algorithm assumptions degrades overall accuracy to 0.59 kPa. ET model results for four flux towers are similar to observed tower fluxes ($r>0.7$; $P<0.003$; RMSE <32W/m^2) and capture regional patterns and seasonal variability in ET and associated temperature and moisture controls on canopy stomatal conductance. Our results indicate significant potential for regional mapping and monitoring of daily land surface ET using synergistic information from current and planned satellite optical and microwave remote sensing inputs.

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Temperature and Humidity Retrieval Results by Land Cover

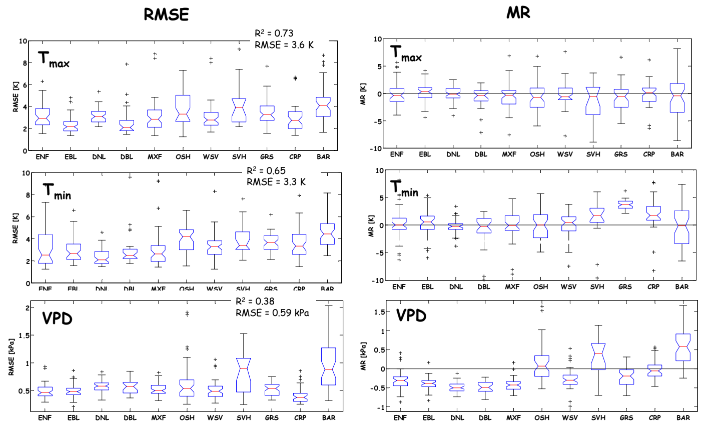

Figure 1: Maximum daily air temperature (Tmax), Minimum daily air temperature (Tmin), and vapor pressure deficit (VPD) results for WMO weather stations for 2003 (See Study Sites). Box plots represent the median with quartiles shown in blue and red, respectively and outliers are black '+'. Results are given for open water free land pixels, screened for precipitation, and limited to May 30 to Sept. 7 for locations above 35° N latitude. Sites were evenly spatially sampled (28-51 locations for each land cover type) out of a total number of 4684 stations. The overall average statistics across sites are reported on top of the left hand side figure panel column. The temperature retrieval algorithm is a forward radiative transfer approach that uses smoothed polarization ratio and channel gradients to correct for biomass/surface roughness and is based loosely on ref. [1]. The VPD algorithm is developed in ref. [2]. R^2= coeff. of determination; RMSE = root mean square error; MR = Mean Residual (Pred. – Obs.). See Study Sites for land cover key abbreviations and study site locations.

ET Model Results

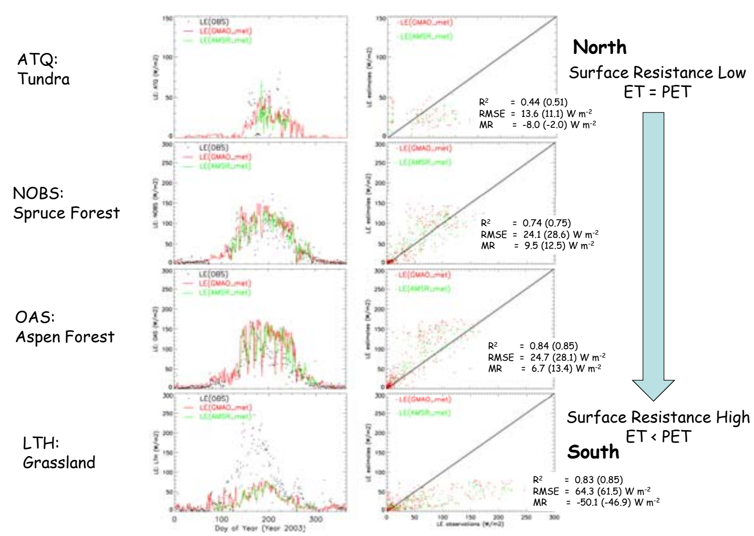

Figure 2: Latent energy flux (LE; W m-^{2}) results above represent a latitudinal transect of flux tower locations for 2003 (See Study Sites). AMSR-E derived temperature and humidity inputs replaced GMAO operational meteorology for the non-frozen period (See Data Flow). Estimates with AMSR-E meteorology are shown in green, estimates with GMAO operational meteorology are shown in red, and observed tower fluxes are black dots. Statistics for each site are given for AMSR-E and GMAO (in parentheses). The overall averages across sites were R^2 = 0.71 (0.74), RMSE = 31.7 (32.3), MR = -10.5 (-5.8). The ET model was developed for global application in refs. [3,4]. See fig. 1 for statistical abbreviations.

ET Algorithm Data Flow

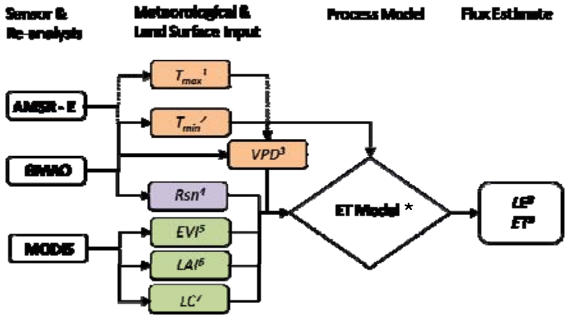

Figure 3: Sources of input data and corresponding ET model estimates. The standard operational meteorology for the ET model is provided by GMAO. AMSR-E data replaces GMAO T_{min} and *VPD* information in the model (dashed lines). R_{sn} provides information on total available energy, *VPD* provides evaporative demand, T_{min} provides the saturation vapor pressure curve derivative and the remaining information provides surface resistance information. Key to abbreviations: [1] Maximum daily air temperature (°C); [2] Minimum daily air temperature (°C); [3] Vapor Pressure Deficit (kPa); [4] Net incoming solar radiation (W m^{-2}); [5] Enhanced vegetation index (dim); [6] Leaf Area Index (m^2 m^{-2}); [7] Land Cover (type); [8] Latent Energy (W m^{-2} d^{-1}); [9] Evapotranspiration (mm d^{-1}). *See ref. [3].

Meteorological Data Sources

- **Advanced Microwave Scanning Radiometer on EOS Aqua (AMSR-E):** Level 2a (60 km x 60 km resolution) multi-frequency (6.9 – 89 GHz) dual-polarization (H,V) brightness temperature ref. [5] footprints were interpolated to a 25 – km EASE grid and grid cells were extracted over each study location. Data are from both descending (AM) and ascending (PM) overpasses, corresponding to ~3am and ~3pm local time. Data were obtained from Steven Chan at JPL and are also used in the AMSR-E Level 3 soil moisture product.
- **Global Modeling and Assimilation Office (GMAO) reanalysis:** Model data interpolated to 1-km resolution ref. [6] from 1.0° lat. x 1.25° lon. grid and extracted in 3 km x 3 km windows centered on each flux tower location.

Study Domain and Test Sites

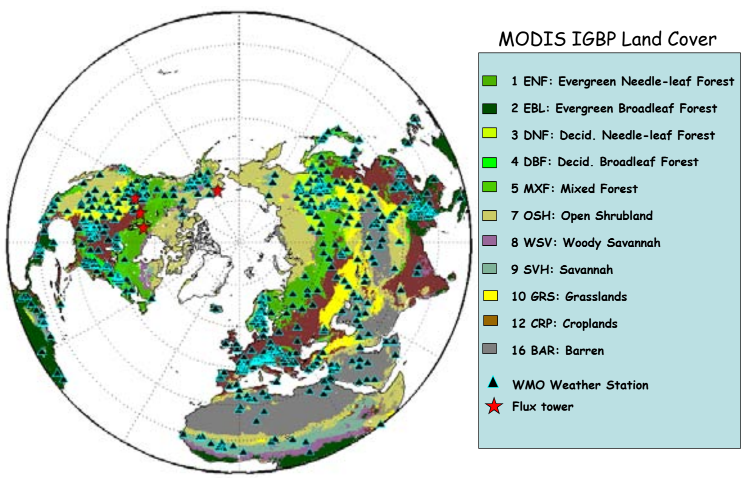

Figure 3: Northern hemisphere study region with tier 1 (flux towers) and tier 2 (WMO weather station) study sites.

Surface Observations

- **Tier 1, Flux Towers:** Data collected by four eddy-covariance flux towers and hydrologic monitoring station instrumentation including: 30-minute or 1-hour air temperatures, precipitation and relative humidity. Data were aggregated to daily values. See acknowledgements for site investigator credit.
- **Tier 2, WMO Weather Stations:** Daily summary of the day surface meteorology for 453 World Meteorological Organization affiliated stations. Variables include Tmax, Tmin, dewpoint temperature (used to calculate VPD), and precipitation.

Humidity Sensitivity to Error in Surface Air Temperature

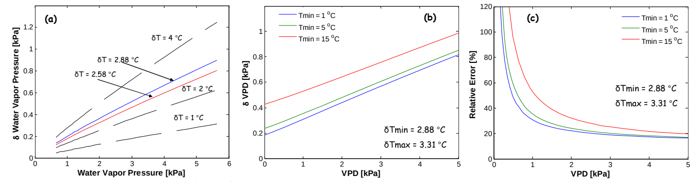

Fig 5: Error propagation analysis for the AMSR-E VPD algorithm. Errors in Tmax and Tmin are assumed independent and randomly distributed. **(a)** Error (δ) introduced to water vapor pressure estimates due to uncertainty in air temperature (δT) from equation (2). Blue line represents Tmin error (Table 2) and red line represents Tday error from equation (1). **(b)** Error introduced to daily vapor pressure deficit at constant levels of minimum daily air temperature with varying mean daily air temperature. Error levels in Tmin and Tmax are held at levels determined for AMSR-E for the four flux tower locations (fig. 4). **(c)** Relative error in daily vapor pressure deficit corresponding to absolute error displayed in (b).

ET Model Sensitivity to Input Meteorology Error

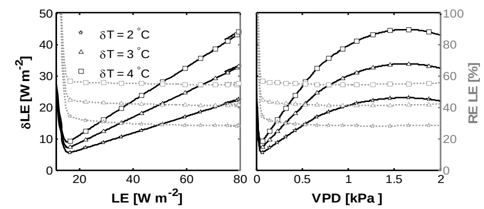

Figure 6: Absolute error (solid black lines; W m^{-2}) and relative error (dashed gray lines; %) propagated to RS-ET estimates of latent energy flux (LE) for three levels of error in remotely-sensed temperatures. Leaf area index, dew point temperature, net incoming solar radiation, and error in net incoming solar radiation are held at constant, moderate values of 3 m^{-2}m^{-2}, 0 °C, 300 W m^{-2}, and 70 W m^{-2}, respectively. Tmax varies from 0 to 30 °C. Soil evaporation is considered negligible (ref. [4].);

Key Findings

Temperature Retrieval:

- Maximum and minimum daily air temperature can be derived to an accuracy of 2-4 °C for open water free scenes across diverse land covers at 453 WMO weather stations (figs. 1, 3).
- Emissivity is remarkably stable across vegetation types and the influence of biomass on emissivity can be described with a relatively simple relation to the polarization ratio for open water free scenes.
- The highest correspondence of Tb with observed air temperatures is for the 23.8 GHz V-polarized Tb presumably because this frequency is sensing the lower atmosphere in addition to the land surface.
- Error increases for increasing open water fraction and to a lesser extent over low-biomass non-woody land covers.
- The increase in Tb sensitivity to atmospheric water vapor over low emissivity scenes caused by open water limits relatively simple emissivity corrections for open water for ≥18 GHz.

Vapor Pressure Deficit Estimation:

- Vapor pressure deficit has a correspondence of 0.28 kPa for forests and 0.44 kPa for non-forest land covers, though site-specific bias degrades overall accuracy to 0.59 kPa (fig. 1).
- VPD is under predicted by ≈0.45-0.50 kPa using the Tmin=Tdew assumption for arid land covers and over predicted by ≈ 0.48 kPa for forest and croplands.

ET model Results:

- AMSR-E provides ET estimates with an average accuracy of 31 W m^{-2} for a transect of four flux towers spanning 50 ° to 71 ° N latitude (fig. 2, 3).
- AMSR-E produces ET model accuracies are on par with estimates derived using the operational GMAO meteorological drivers (fig 2).
- AMSR-E retrieved thermal information is promising for monitoring water and energy fluxes as well as providing important land surface wetness status in high-biomass locations where direct soil moisture sensing impossible with current microwave technology (fig. 5,6).